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Effect of reduced ignition propensity paper bands on cigarette burning temperatures

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ABSTRACT

An experimental study was conducted to examined the combustion behaviour of reduced ignition propensity (RIP) cigarettes during smouldering and puffing phases. The internal gas-phase temperature of the burning tip (or coal) was systematically measured by using arrays of fine thermocouples accurately inserted around the RIP band. Both temperature and temperature gradient contours at up to 10 Hz were digitally constructed. The results revealed for the first time that the RIP band caused a marked change in the temperature distribution patterns under puffing. The band was also able to suppress smouldering well ahead of the approaching coal. The temperature gradient contours demonstrated the changes in the extent combustion, mostly caused by modification to the air influx during puffing. The coal volume fractions at different temperatures were quantified and compared to a non-RIP control cigarette. Possible implications of the observations on RIP cigarettes ignition testing and smoke composition were discussed.

1. Introduction

Burning cigarettes can cause fire. Cigarette-related fires are one of the leading causes of property loss, injuries and fatalities [1–3]. US Congress, through the Cigarette Fire Safety Act of 1984, initiated research aimed at determining the feasibility of developing a more fire-safe cigarette. New York State was the first state to enact legislation in 2004, which required all cigarettes on sale to pass an ignition propensity performance standard as tested by the ASTM E2187 standard method. This legislation has been implemented in other US states, and also countries such as Canada, Australia, New Zealand, South Africa, and most recently European Union member countries.

The New York regulation specifies the use of 10 layers of Whatman No. 2 filter paper as the test substrate. 40 replicate cigarettes of a given brand are tested in a draft-free chamber and the brand is compliant if <25% of the tested cigarettes exhibit full-length burn, i.e., ≥75% of the tested cigarettes self-extinguish in the test. It does not specify what kind of technology a manufacturer should use to meet the performance standard. Although work in the 1980s and 1990s concluded that a cigarette's ignition propensity could be reduced by modifying some physical or blend parameters of the cigarette [4,5], the use of cigarette paper printed with biopolymer-based bands (5–6 mm wide, with around 20 mm inter-band distance, randomly distributed along the tobacco column) became the dominant approach for commercial cigarettes [6]. The presence of the RIP bands is mainly designed to reduce a cigarette's smoulder ability, either in free burn or when the cigarette is on a substrate. However, adjustments to the base cigarette paper are normally necessary to ensure the overall mainstream smoke chemical composition or yield is not adversely affected by the incorporation of RIP technology.

The main thermophysical processes involved in a burning cigarette without RIP features have been extensively studied [7–10]. Temperature distributions inside a burning cigarette, arguably one of the most fundamentally important parameters governing both its ignition propensity during smouldering and also the smoke composition during puffing, have been systematically mapped. During puffing induced by external flow, solid-phase and gas-phase temperatures have to be measured separately [7–9]. The two temperatures only reach equilibrium during steady-state smouldering. Gas-phase temperatures are commonly (but not routinely) measured using fine thermocouples inserted inside a tobacco rod. In contrast, measuring the solid-phase temperatures inside the burning coal requires the use of fine infrared probes [8,9]. The gas-phase temperature is linked to gas viscosity and pressure

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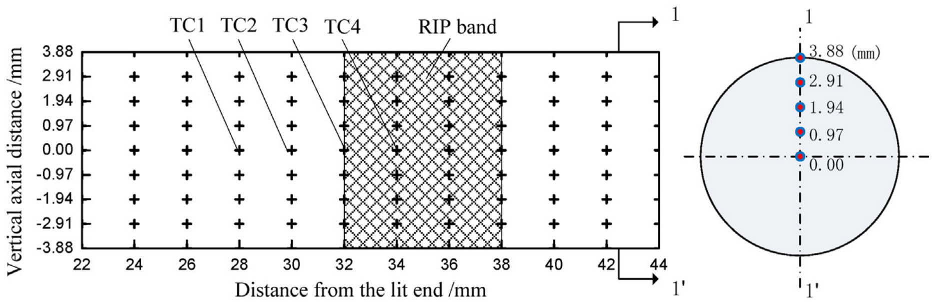

Fig. 1. The thermocouple insertion position (location and depth) along a cigarette rod and in relation to the RIP band.

drop within the tobacco rod [11], and therefore a key factor controlling the mass transfer and aerosol dynamics within the cigarette.

Some studies have been conducted on RIP cigarettes in order to understand, for example, the effects of cigarette design parameters on RIP test performance [12], smoke chemistry under machine-smoking conditions [13], and human smoking behaviour [14,15]. A significant increase (14.3–23.5%) in the levels of three PAH biomarkers in smokers was noted post RIP cigarette introduction [6,13], although the toxicological implications of these increases are currently unknown. The mechanistic principles behind RIP-influenced changes in cigarette smoke chemistry are not clear. There has been little detailed thermophysical examination of how RIP bands affect the way RIP cigarettes burn. In this work, accurate and reproducible measurements of the temperature profiles within the RIP cigarette were conducted by thermocouples, especially around the RIP band region.

2. Material and methods

2.1. Thermocouple insertion

K-type thermocouples of 0.254 mm (Omega Engineering Inc., Connecticut, USA) were inserted into pre-defined positions around the RIP band (Fig. 1). The band positions on commercial RIP cigarettes are randomly distributed and not visible to the naked eye. Cigarettes were selected with an RIP band between 30 and 35 mm from the lighting end, approximately the middle of the tobacco rod of 58 mm length. Identification of RIP band position was achieved by painting the tobacco rod with a soft brush carrying a small amount of distilled water; this process temporarily revealed the band position without affecting the physical and chemical integrity of the cigarette, which was then marked with a soft pencil. The marked cigarettes were conditioned for at least 48 hr before testing. To limit any potential interference in the cigarette combustion the presence of thermocouples, a maximum of 8 thermocouples were inserted in a single cigarette. The thermocouples were separated in 2 mm gaps along the rod length direction. Cross-sectionally, 5 insertion depths were selected as marked in Fig. 1 on the vertical axis. Due to the axial symmetry of the tobacco rod (horizontally positioned), only one side needed to be measured. After the thermocouples were inserted, a small amount of starch-based paper glue was applied to seal any air leakage around the thermocouple insertions.

2.2. Data collection and graphic representation

A high-speed analogue-to-digital converter (Omega Engineering Inc., Connecticut, USA) was used to capture the outputs from the thermocouples at a recording frequency of between 10 and 50 Hz for each thermocouple. The outputs from individual thermocouples at a location were obtained and can be displayed (Fig. 2(A); the different depth corresponding the y-axis grid shown in Fig. 1). Systematic evaluation on the relative standard deviation on temperature measurements were conducted using the technique described (Fig. 2(B)). Because the fine thermocouples used were not fixed inside the burning coal, puffing flow was found to have an impact on the relative standard deviation and the averaged over 4 replicates were used in this work to provide an acceptable level of errors associated with the technique. For visual overview of all the measurements, the temperature outputs were digitally reconstructed to produce a series of temperature contours or maps. For this purpose, interpolation of temperature readings between measurements were achieved numerically following the bi-cubic interpolation algorithm. A be-spoke software routine written in MATLAB (http://www.mathworks.co.uk) performed this task and produced the temperature maps. The software also calculated the volume fractions corresponding to a set temperature range. This

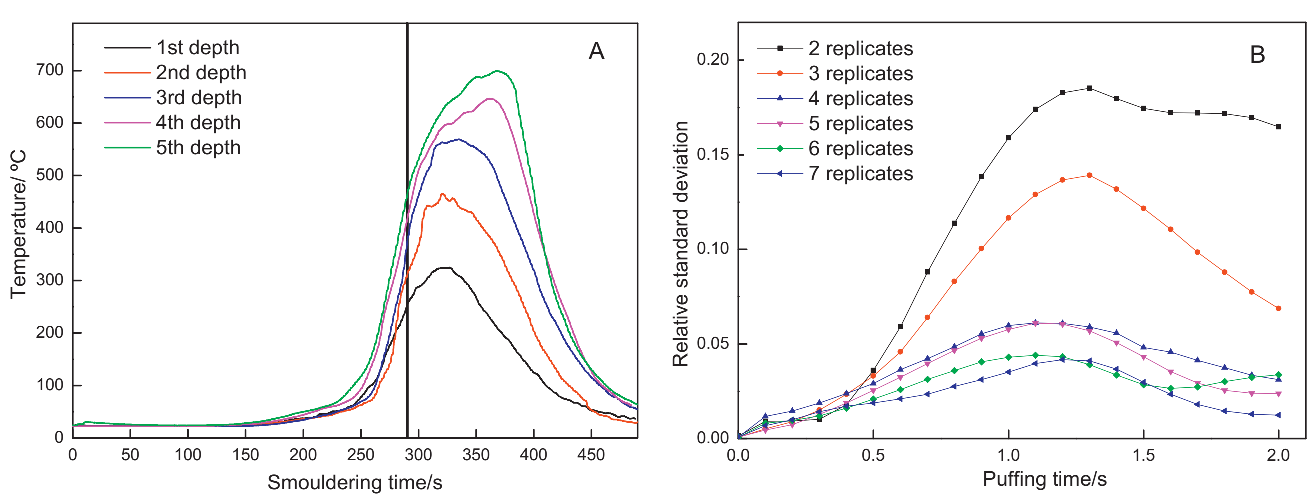

Fig. 2. An example of the thermocouple outputs at different depth of the tobacco rod (A) and calculated typical relative standard deviation (B).

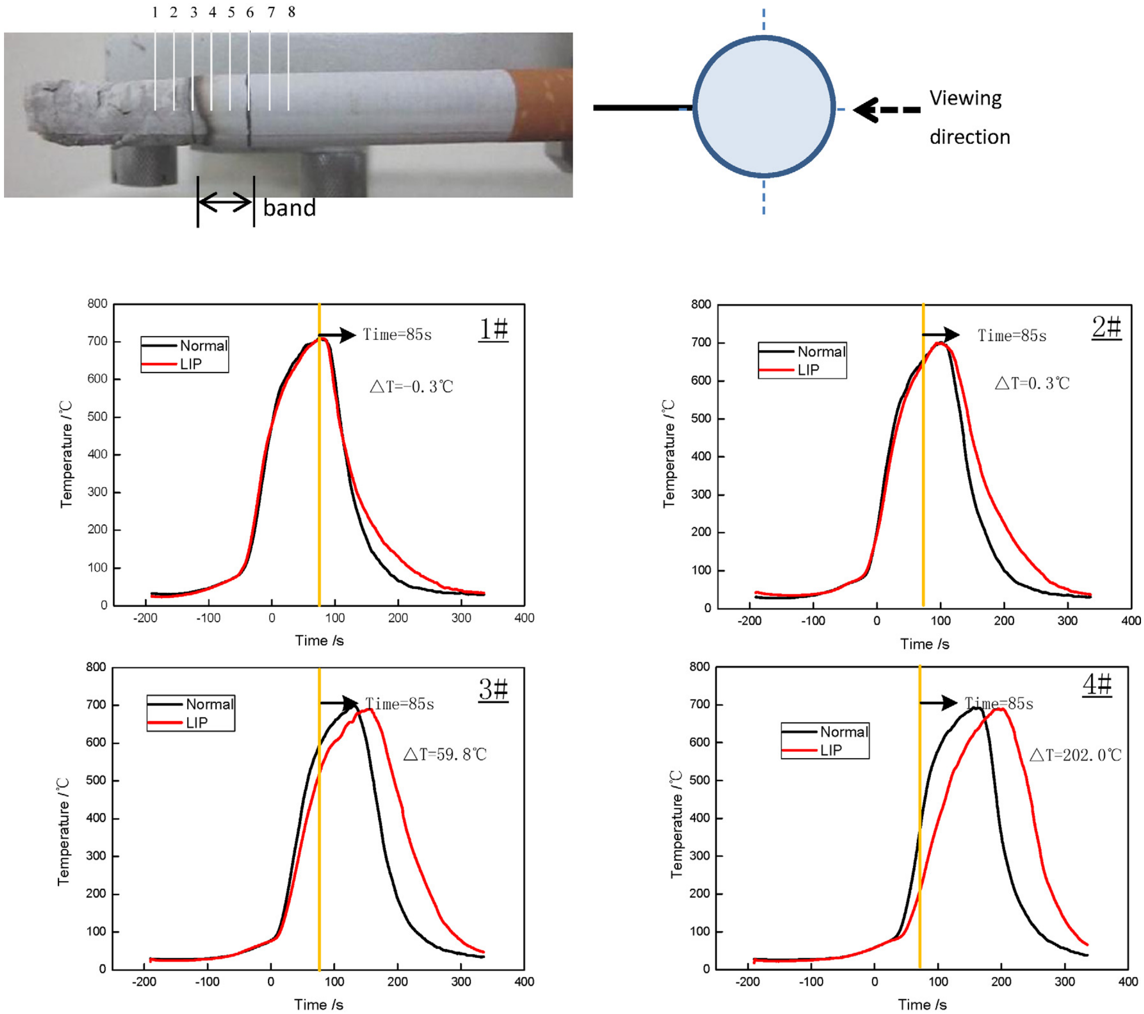

Fig. 3. Temperature profiles at four central axial locations around the RIP band (only the RIP cigarette is shown). The RIP band position marked with a soft pencil, starting from position 3 and finishing at position 6.

information was used to compare gas-phase temperatures as a function of puffing time and the cigarette designs (RIP vs. non-RIP).

To complement the gas-phase temperature measurements, peripheral solid-phase temperatures were also measured by an infrared thermal camera (G90, SATIR, China) at a recording frequency up to 25 Hz. Details of the test procedure was similar to that reported previously [16,17].

2.3. Test cigarettes and smoking procedure

Two types of test cigarettes were used in this study. They had an identical tobacco blend (a Virginia type without any flavouring agents) and construction, Differing only in the cigarette papers used. The base paper permeability are 60 CORESTA unit (CU, which is defined as the air flow ($cm^3\,min^{-1}$) passing through a 1 cm^2 of test material at an applied pressure of 1.00 kPa). Both has a burn additive (a mixture of Na- and K-citrate) and used hemp as paper fibre. For the RIP paper, the band diffusivity was specified as 0.30 $cm\,s^{-1}$, with the band at 6 mm in width and 18 mm in between the band. The test cigarettes were weight-selected to be within ±5 mg and conditioned at 22 °C and 60% Relative Humidity for at least 48 h before testing.

A single-port smoking machine (AIOFM, Anhui Province, China) provided the required smoking parameters (35 mL puff volume, 2 s puff duration and one puff every 60 s) as defined by ISO standard: 3308 (2012) (Routine analytical cigarette-smoking machine - Definitions and standard conditions).

3. Results

3.1. Effect of RIP band on smouldering temperatures

In Fig. 3, temperature responses from four thermocouple (TC) inserted into the central axial positions are displayed in pairs (RIP vs. non-RIP) to illustrate the effect of the RIP band at the axial central locations. The horizontal axis in Fig. 3 is the recording time and its full range was selected to cover the four TCs' output without a specific meaning for the time $t = 0$ s. Previous work has shown that fine thermocouple measurements as used in this type of study can display relatively large variations [8], and levels of variation around ±30 °C are not uncommon. In this study, the weights of cigarettes and the TC insertion were carefully controlled to minimise variations. The four TCs were positioned 2 mm apart with TC3 matching the front edge of the RIP band. During smouldering the axial central location is the furthest point cross-sectionally from the paper wrapper, hence any effect caused by the change in paper porosity (e.g., by the RIP band) as measured by the TCs would have impacted on the rest of the burning regions before reaching the central locations.

As can be seen in Fig. 3, the outputs from TC1 positioned at 4 mm ahead of the RIP band gave nearly identical responses for both cigarettes, indicating no detectable influence of the RIP band in the centre of the tobacco rod. During smouldering, the thermocouples measured both the gas- and the solid-phase temperatures. Using the almost identical peak temperature of ca. 709 °C for the two TCs achieved at t = 85 s as a reference point (the vertical yellow line), a gradual temperature lag for the RIP cigarette appeared to build up from TC2 to TC4. The responses by TC4 showed that the RIP cigarette had ca. 200 °C lower temperature than that of the non-RIP cigarette at the yellow vertical line. In fact the temperature difference for TC4 already began to emerge some 20 s before the mark. The final time delay of ca. 10.2 s for the RIP cigarette in reaching its peak temperature could be used to calculate an average burn rate within the banded region to be ca. 3.1 mm min^{-1}, much lower than the 4.6 mm min^{-1} for the non-RIP cigarette. No significant difference in the peak temperature or the rate of temperature rise was observed for the two cigarettes. The temperature responses from the remaining thermocouples (TC5 to TC8) for the RIP cigarette followed further delays to reach its peak as compared to the non-RIP cigarette: ca. 49s, 58s, 70s and 60s for TC5 to TC8 respectively (temperature profiles not shown). The maximum time lag occurred between TC6 and TC7; from TC7 and TC8 the time difference began to reduce as the RIP cigarette burned through the band. This supports the common belief that the RIP band functioned as a “speed-bump” in reducing the cigarette’s propensity to smoulder at the band positions [6].

3.2. *Effect of RIP band during puffing*

The overall effect of the RIP band could be further examined by reconstructing cross-sectional temperature distribution maps as shown in Fig. 4 before, during and after a 2-s puff. In Fig. 4, the x-axis displays the distance (mm) from the tip of the cigarette and the time t = 0 is the moment when the RIP cigarette’s paper burn line (PBL) reached approximately 2 mm ahead of the left (start) edge of the RIP band. Both RIP (left) and non-RIP (right) temperature maps are given in pairs.

At 18.9 s before the puff the RIP cigarette and the non-RIP had almost identical temperature distributions (Fig. 4(a)), which are also similar to that reported previously [9]. Immediately before puffing (t = 0 s), the total burn volume above 200 °C (shown in Fig. 4(b) by the lowest and the peripheral temperature contour line) was similar for the two cigarettes. However, the central region of the RIP cigarette had a lower temperature with a somewhat reduced volume between 600 and 700 °C. This is a clear indication that the RIP band functioned as intended even before the paper burn line reached the edge of the RIP band.

As the smoking machine took a 2-s puff, it exerted a bell-shaped air flow of 35 mL, with the largest amount of air entering around the burning tip (small amount of air was also drawn through the cigarette paper). At 1 s into the 2 s puff, which corresponded to the moment of the highest air flow into the cigarette, Fig. 4(c) shows that the RIP cigarette developed a markedly different temperature contour as compared to that of the non-RIP cigarette. For the non-RIP cigarette, the most obvious change from Fig. 4(b and c) is the enlargement of the inner high temperature region with its high temperature contour drawn towards the direction of the air influx around the immediate vicinity of the paper burn line [8]. In the case of the RIP cigarette, there was also a noticeable increase in the inner higher temperature volume but the pattern of the higher temperature contour appeared to truncate at the tip, indicating a significantly altered air influx path as compared to the non-RIP cigarette.

At the end of the 2-s puff (Fig. 4(d)), clear differences remained to be seen in the temperature patterns for the two cigarettes despite the termination of the forced air flow: for the RIP cigarette the volume of the inner region with the high temperature began to decrease and this region was surrounded by a slightly higher temperature shell, which is absent from the non-RIP cigarette. Visually the overall shape of this inner high temperature region is narrower but longer for the RIP cigarette. From this moment onwards, the gas-phase temperature and solid-phase temperature moved towards an equilibrium as there was no further external air perturbation.

To compare the surface solid-phase temperatures of the two cigarettes during puffing, an infra-red camera was used to view the external cigarette temperature changes. The infrared thermal images obtained at 1 s into the 2-s puff (corresponding to Fig. 4(c)) are shown in Fig. 5 for the two cigarettes. The thermal images are given in pairs with the top images showing the as-viewed infrared thermographs and the bottom images showing the processed temperature-interval profiles to allow easier comparison. The non-RIP cigarette appeared to show a slight bend downwards at the tip; this might be related to the build-up of ash in this specific case. On the whole the bright orange coloured regions for both cigarettes indicated the high temperature burning occurred immediately in front of the paper burn line. Two additional features may be worth noting. The first feature is that the bright high temperature region of the RIP cigarette showed a relatively vertical and more uniform edge in front of the paper burn line, while the high temperature region for the non-RIP cigarette appeared to be more varied in relation to its paper burn line. The second feature is that the RIP cigarette had a higher surface temperature (better viewed by the two thermal images given in temperature intervals) and the high temperature region was further away from the paper burn line.

Table 1 compares quantitative results from the two cigarettes concerning the relative volume fractions corresponding to selected temperature ranges. These give more detailed temperature comparison than possible with the visual representation (Figs. 4 and 5). It confirms that at 18.9 s before the start of the puff, no significant difference could be found for all the volume fractions. Small but consistent decreases in the volumes began to emerge with the RIP cigarette at t = 0 s. During the puff (reflected by the 1 s and 2 s measurements), RIP cigarettes had consistently lower volumes for all the volume fractions except for the fraction above 600 °C, which were similar for the two cigarettes.

Fig. 6 illustrates the continuous evolution in the total burn volume at equal or greater than 200 °C as a function of the burn time. The time zero in this case coincided with the start of the 2-s puff. A clear and gradual decrease in the burn volume for the RIP cigarette appeared to be established soon after 18.9 s before the puff. The sharp and almost linear increase in the temperature volume peaked at the end of the air flow. The volume difference established before the puff continued more or less unchanged throughout the puff. A pseudo-linear decrease in the temperature volume after the end of the puff was followed by the two cigarettes in an approximately parallel manner.

4. Discussion

In this work, the bare thermocouples inserted into the cigarette were likely to be in physical contact with tobacco strands. However, as Baker pointed out, the measured temperature reflects mainly the gas-phase temperature during puffing and the equilibrium gas/solid-phase temperatures during steady-state smouldering [9].

Mechanistically the results obtained in this study showed at least two significant temperature modifications were caused by the RIP band. The effects were highlighted by examining in detail the region close to the RIP band and the transition from smouldering to puffing. During smoulder, Fig. 3 show that the two types of cigarettes burned in almost the same way until the paper burn

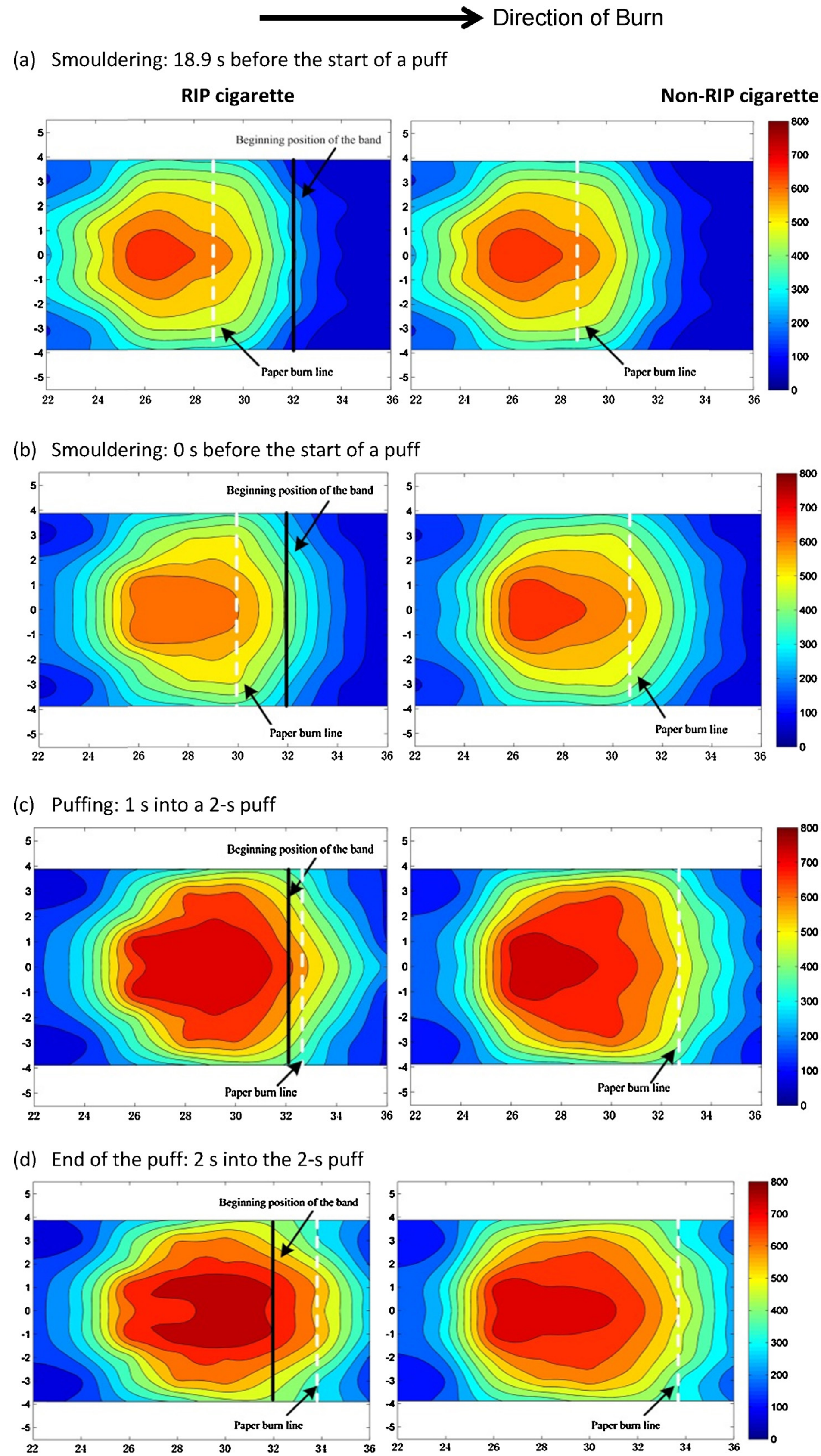

Fig. 4. Temperature contours from the RIP and non-RIP cigarettes at different time of the 2-s puff.

Table 1
Gas-phase temperature volume (mm^3) at different temperature ranges for the two types of cigarettes.

Times	≥200 °C		≥300 °C		200–400 °C		400–600 °C		≥600 °C	
	RIP	Non-RIP	RIP	Non-RIP	RIP	Non-RIP	RIP	Non-RIP	RIP	Non-RIP
−18.9	459.6	459.9	348.2	348.2	235.0	236.0	202.3	201.8	22.3	22.1
0	456.0	474.8	343.2	364.2	235.8	239.8	195.7	204.2	24.5	30.8
1	495.7	521.2	396.1	419.7	191.3	205.7	171.6	184.1	132.8	131.5
2	550.7	571.4	457.3	474.4	191.9	197.7	201.9	217.1	157.0	156.6

line approached the front edge of the RIP band. The majority of the change produced by the RIP band appeared in the inner central region (Fig. 4(b)). The most sensitive reflection of the change was provided by comparing the volume of heated regions inside the burning coal (Fig. 6), starting at ca. 19 s ahead of puffing. The observed change could only be achieved by the RIP band restricting oxygen availability from the unburnt paper direction, because prior to the puff there was no difference between the two types of cigarettes in the opposite direction. This phenomenon is known for conventional cigarettes [8], and has been reported as an additional and enhanced effect with RIP cigarettes [12], aimed at further limiting the cigarette's tendency to smoulder. However, quantitative confirmation as to the time of onset was only revealed by this work.

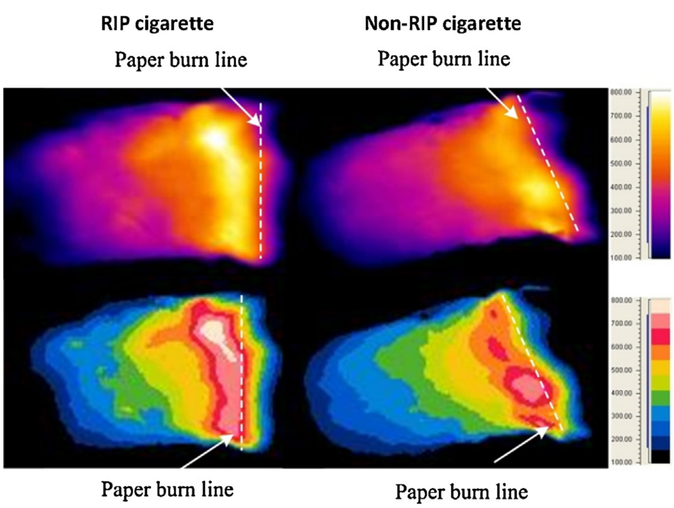

Fig. 5. Infrared peripheral solid-phase temperature distribution at 1-s into the 2-s puff (corresponding to the observation shown in Fig. 4(c)).

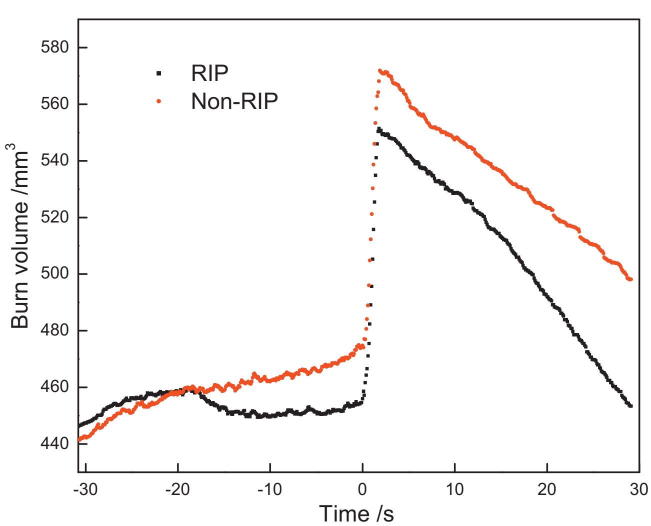

Fig. 6. The total coal volume above 200 °C as a function of time around the 2-s puff.

The second mechanism by which the RIP band affects puffing may be better explained by the illustration drawn in Fig. 7, which displays the temperature gradient maps (dT/dt) for the temperature results shown in Fig. 4(c). A higher temperature gradient region reflects a greater extent of combustion (oxidation) process, hence indirectly linked to the influx of oxygen (and air flow). During puffing, the paper burn line moved approximately 0.5 mm into the RIP band (Fig. 7 left). In a non-RIP cigarette, Baker's earlier work showed that the highest air influx occurs around a small region immediately behind the freshly charred paper burn line, rather than from the tip of the coal or ahead of the paper burn line. This is because in this way the incoming air bypasses the highest thermal viscosity region and flows into the tobacco rod through the least resistive route [8,9]. In Fig. 7, proposed air flow patterns are superimposed onto the two clearly different temperature gradient distribution maps.

For the RIP cigarette at 1 s into the puff (Fig. 4(c)), the temperature contour was very different. This contour could only physically be possible due to a change in the air influx path, as all the other cigarette design features of the two cigarettes are identical. Although direct air flow measurements have not been measured in this study, the air flow vectors (as indicated by the direction and thickness of the arrows in Fig. 7) were pushed towards the direction of the burning tip and away from the paper burn line (Mechanism 2). This agrees qualitatively with the infrared thermal images (Fig. 5). This mechanism is feasible because the RIP band carries more and denser material than a normal cigarette, and even after burning the band still maintains a higher resistance to air flow than conventional cigarette paper. Therefore this modified gas-phase temperature pattern is the result of an abrupt transition from smouldering burn in the higher permeability base paper to puffing burn in the much reduced permeability RIP band. This pattern would not have occurred if the tobacco rod was wrapped entirely with either the RIP paper or the base paper (i.e., the conventional cigarette).

Modification of the temperature distribution, as revealed by this work, might be expected to influence the chemical composition of the smoke, although this was not the focus of this investigation. In reality, the position of the RIP bands are randomly distributed along the tobacco rod; hence the chance that the RIP cigarettes are smoked by smoking machines exactly into the band as studied in this work is relatively low. Most of the puffs of a cigarette (from which smoke chemistry is measured) will occur in non-banded areas of the cigarette rod. Hence the smoke chemistry of a banded cigarette paper will be dictated by the puffs taken in the non-banded area of the rod. For example, if two puffs of an eight puff machine smoked cigarette are taken in the area of a band, then only approximately 25% of the smoke chemistry is likely to be influenced by the banded region of the cigarette. If more frequent puffs are taken while the burning is around the RIP band, a situation likely to happen if smokers notices the cigarette is about to go out and hence take additional or bigger puffs around the band to sustain burning, this could exacerbate the situation. Li et al. [18] have observed that mainstream smoke Benzo[*a*]pyrene yields are sensitive to the way the cigarette is lit by different lighting sources, and a possible mechanism forwarded was that different amounts of soot particles (which are known to carry PAHs on their surfaces)were

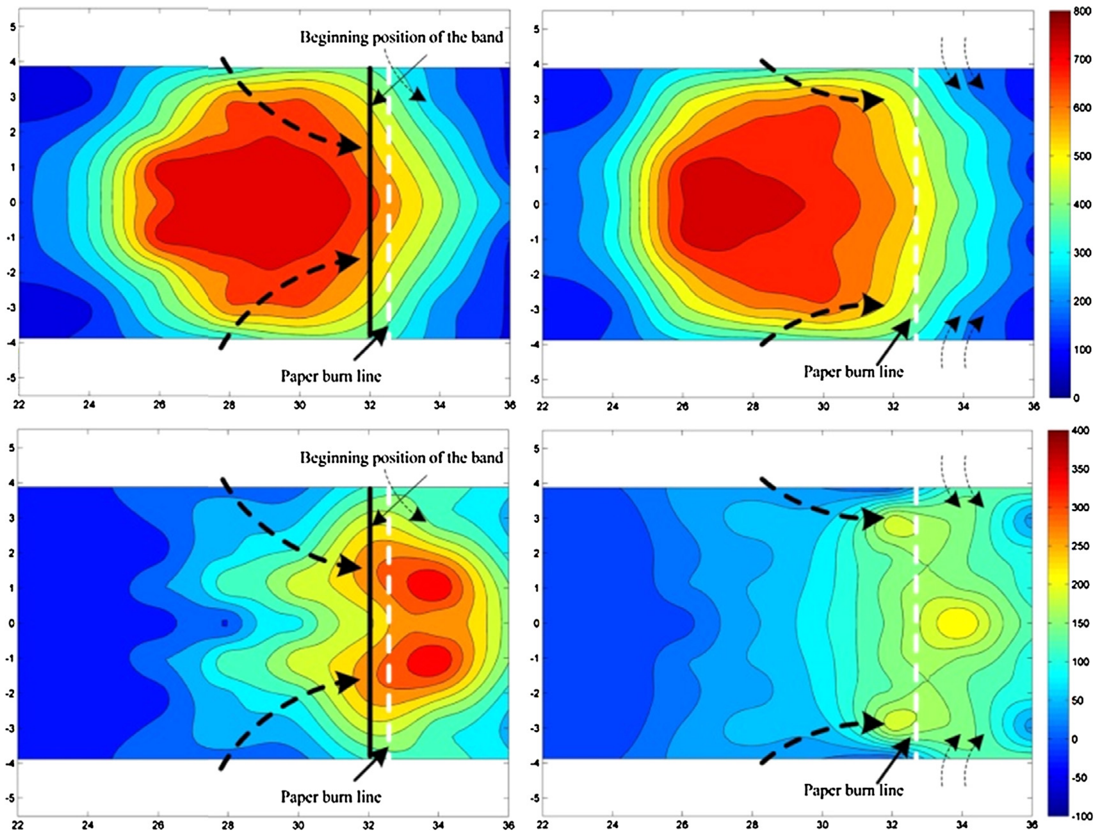

Fig. 7. Comparing the temperature gradient maps to illustrate the modified air flow path by the RIP band (left) during puffing.

formed with the various lighting mechanisms. The change in flow pattern as observed in this work could operate in a similar manner to carry more PAHs formed on burnt tobacco particles into the smoke. This could be the reason behind the observed increases in PAH biomarkers for the smokers using commercial RIP cigarettes [6,13]; further studies are required to either confirm or reject this association.

The direction of the gas flow inside porous solid can be obtained from the internal pressure distribution, since the gas flow is perpendicular to the pressure contour and is towards lower pressures. We will use this principle in the next study to establish the gas flow velocities inside a burning RIP cigarette to further highlight the possible changes made by the RIP band.

5. Conclusion

This experimental investigation fills a gap in our understanding of the way RIP cigarettes burn, as reflected by gas-phase temperature around the RIP band region. A significant modification to the temperature distributions was revealed by different temperature measurements. The gas-phase temperature volume was the most sensitive parameter reflecting the early effects of RIP band in restricting the oxygen availability into the smouldering coal. The marked change in the gas-phase temperature contours indicated that the effect of the RIP band would be significant if cigarettes are smoked into the RIP band, a situation that is practically possible but likely to have only a small influence on the overall cigarette smoke composition.

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